MC support tools 2026
17 Mar. 2026
Durham

StringSpinner: adding spin to Pythia hadronization

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SPINFRAG

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StringSpinner: adding spin to Pythia hadronization

Why spin effects in hadronization?

challenging and fun!

connected to studies of 3D partonic structure of nucleons

lot of data	DIS (COMPASS, HERMES, JLAB)
	e^+e^- (BELLE, BABAR, BESIII)
	pp (RHIC)
new experiments	EIC, JLAB@22 GeV, LHCSpin

Spin in Pythia by StringSpinner

PYTHIA 8

DIS, e^+e^-, pp, pA, ..

spin
DIS, e^+e^-
PS off

StringSpinner (C++, Fortran)

https://gitlab.com/albikerbizi/stringspinner

AK, L. Lönnblad CPC 2023 DIS

AK, L. Lönnblad, in preparation DIS, e+e-

lacks

string+$^3P_0$

AK, Artru, Martin, PRD 2021

AK, Artru, PRD 2024, PRD 2026

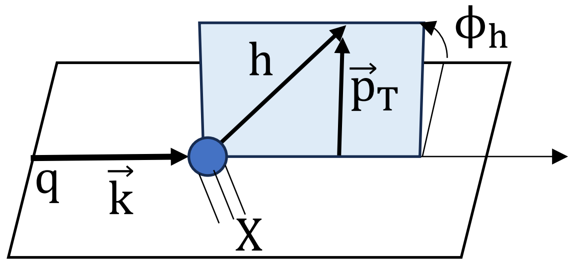
spin effects in hadronization

- Collins effect
- 2h asymmetry
- polarizing FF
- jet handedness
- jet functions.
- ...

«The spin effect» in hadronization

- **Collins effect** in the fragmentation of transversely polarized quarks $z = p^+/k^+$

Collins, NPB 396, 161 (1993)



$$D_{q^\uparrow \to h+X}(z, \vec{p}_T) = D_{1q}^h(z, p_T^2)$$

«The spin effect» in hadronization

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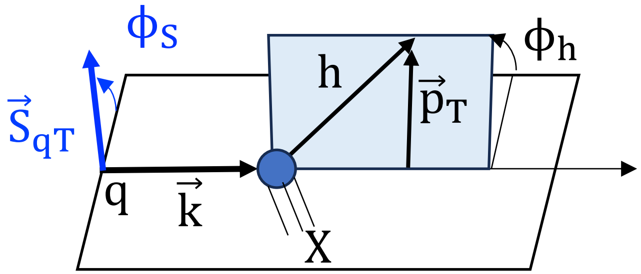


Collins fragmentation function (FF)

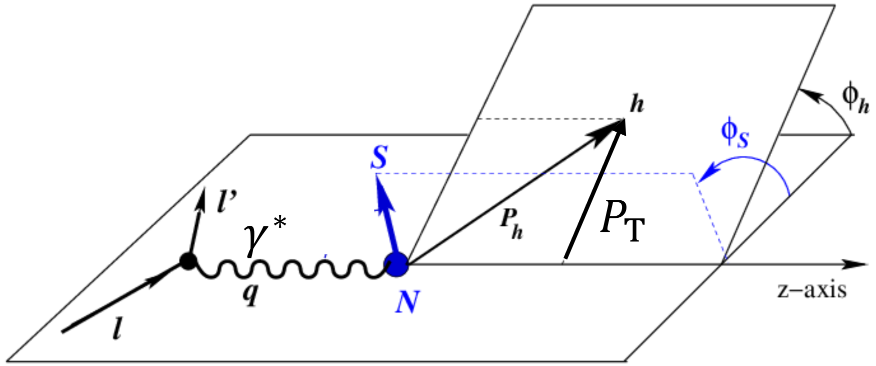
$$D_{q^\uparrow \to h+X}(z, \vec{p}_T) = D_{1q}^h(z, p_T^2) + \frac{H_{1q}^{h\perp}(z, p_T^2)}{zM_h} \vec{S}_{qT} \cdot \hat{k} \times \vec{p}_T$$

- Asymmetric azimuthal distribution
  sensitive to the quark transverse polarization → quark polarimetry!

- Appears in different processes:
  - semi-inclusive DIS (SIDIS)
  - $e^+e^- \to$ hadrons
  - $pp \to hX$

Collins effect in SIDIS: the Collins asymmetry

- Asymmetry in the azimuthal distribution of the observed hadrons in DIS



$$\phi_{Coll} = \phi_h + \phi_S - \pi$$

$$d\sigma^h \propto 1 + D_{NN}\, |\vec{S}_T| A_{Coll} \sin\phi_{Coll} + \cdots$$

$$\mathbf{A_{Coll}} \simeq \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 f_1^q \otimes D_{1q}^h}$$

Transversity PDF h_1^q → transverse spin of quarks in a transversely polarized nucleon

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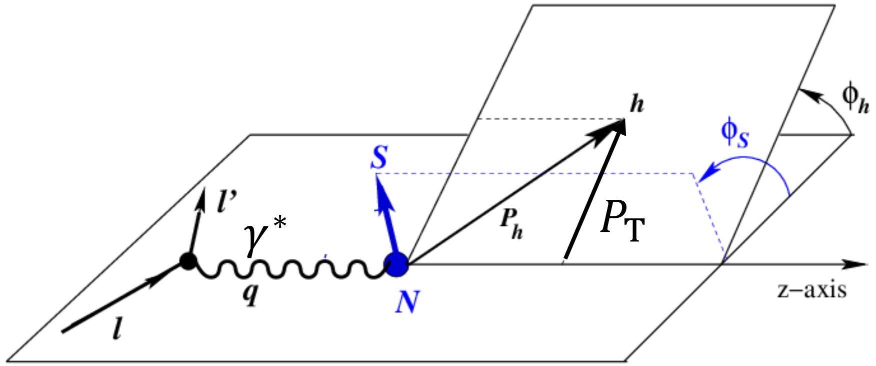

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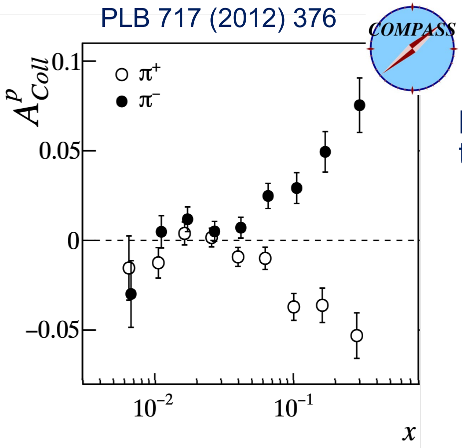
Transversity PDF h_1^q → transverse spin of quarks in a transversely polarized nucleon

- A_{Coll} measured by different experiments (HERMES, COMPASS, JLAB)

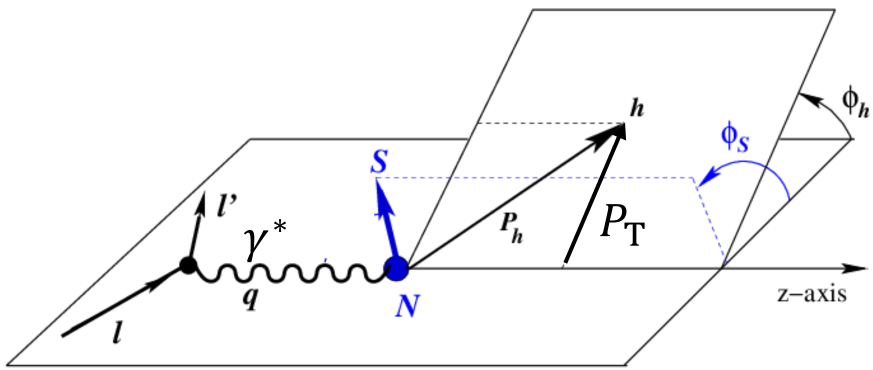
PLB 717 (2012) 376



proton target

Collins effect in SIDIS: the Collins asymmetry

- Asymmetry in the azimuthal distribution of the observed hadrons in DIS



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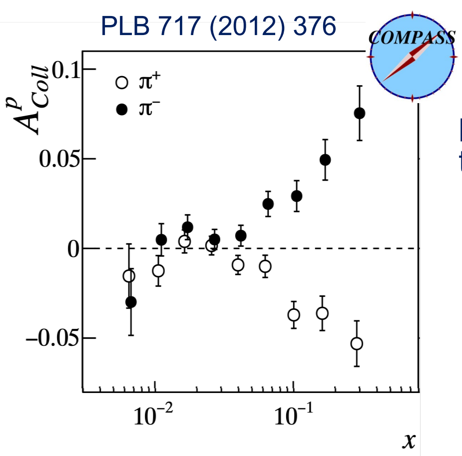
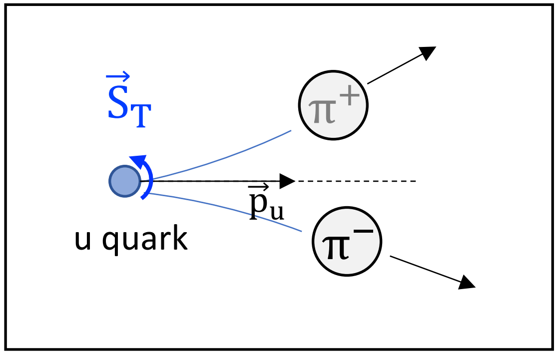


proton target

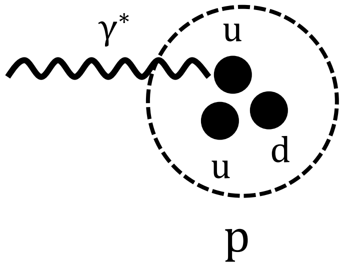
$$A^p_{Coll}(x) \simeq \frac{h_1^u}{f_1^u} \times \frac{H_{1q}^{\perp h}}{D_{1q}^h}$$



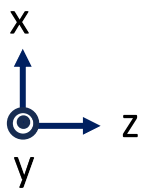
The model for the spin effects: string+$^3P_0$

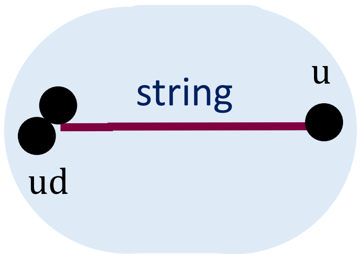
X. Artru [Dubna SPIN 2009], arXiv:1001.1061
AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

String breaking

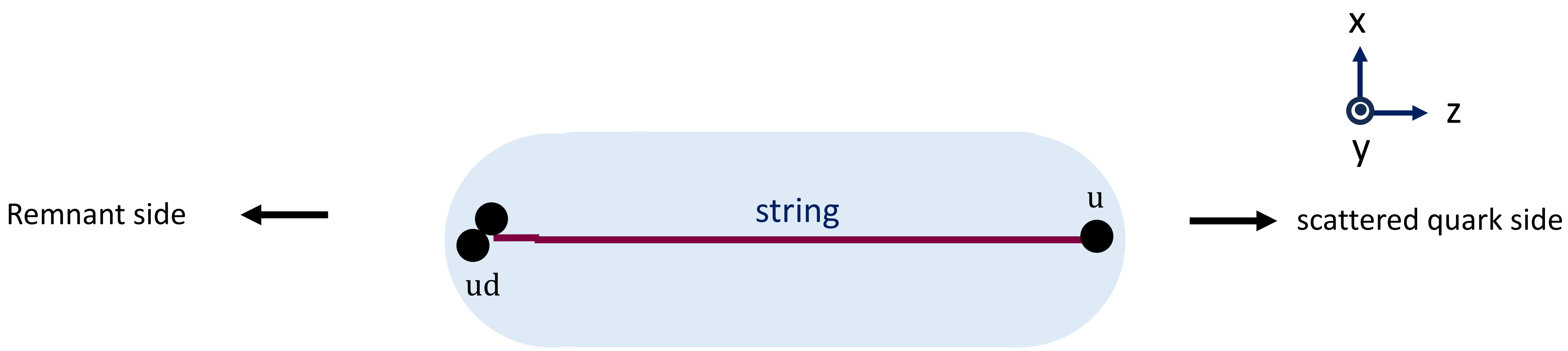


String breaking

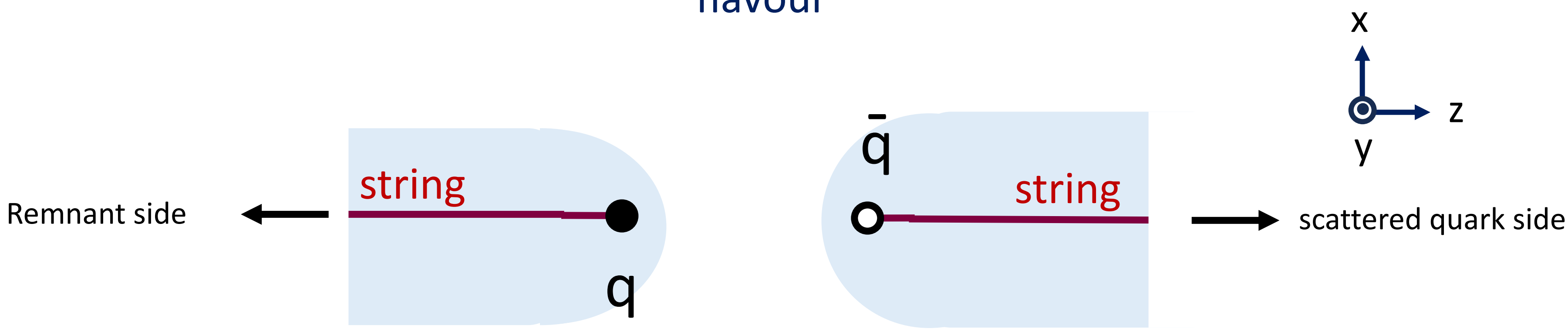




String breaking



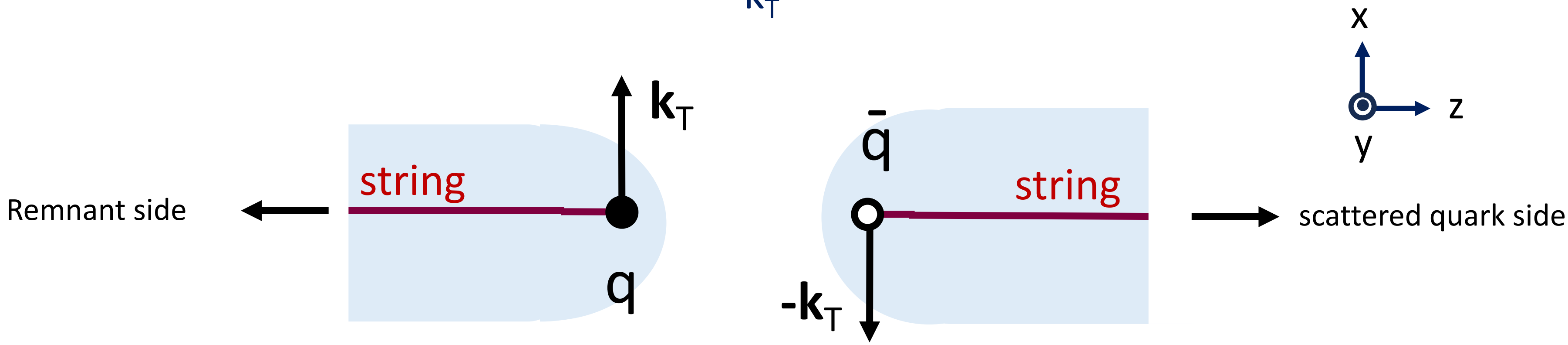
String breaking
flavour



String breaking via $q\bar{q}$ tunneling

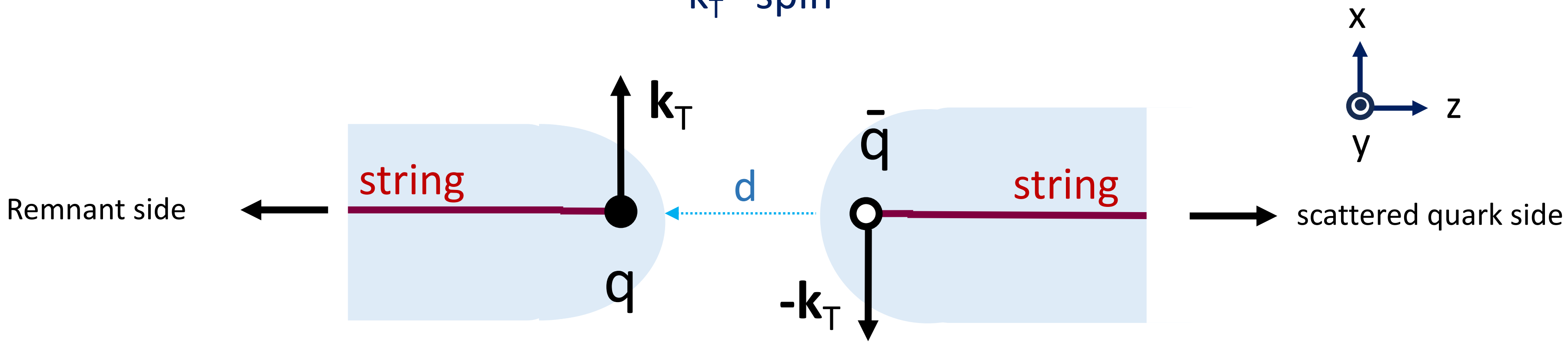
u, d, s quarks produced

String breaking
k_T



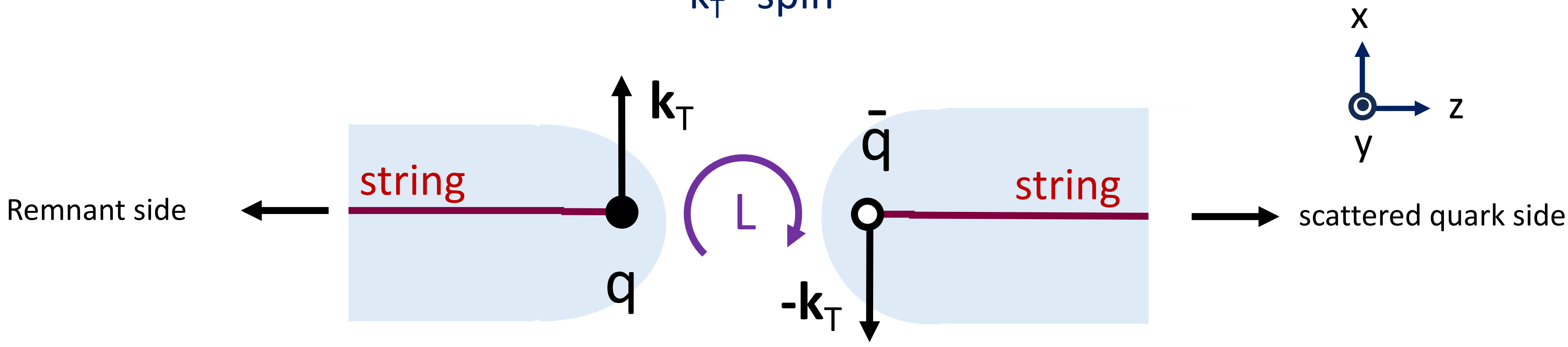
Local conservation of k_T
+ exponential damping [Schwinger mechanism]

String breaking
k_T - spin



The pair is produced at a distance d

String breaking
k_T - spin



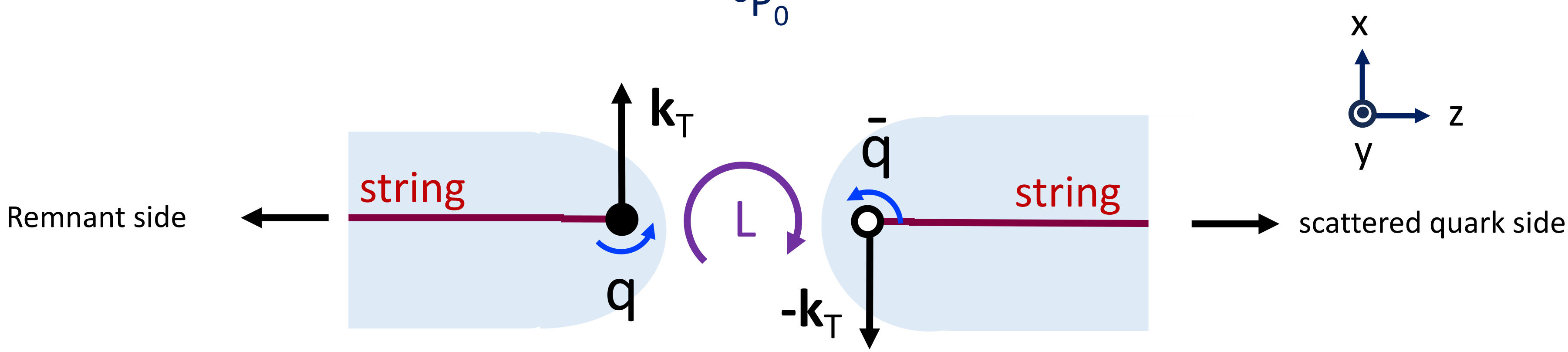
The pair is produced at a distance d

$$\vec{L} = \vec{d} \times \vec{k}_T \neq \vec{0}$$

Local conservation of angular momentum

$$\vec{S} = \vec{S}_q + \vec{S}_{\bar{q}} \neq \vec{0}$$

String breaking
$^3P_0$



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Local conservation of angular momentum

$$\vec{S} = \vec{S}_q + \vec{S}_{\bar{q}} \neq \vec{0}$$

therefore

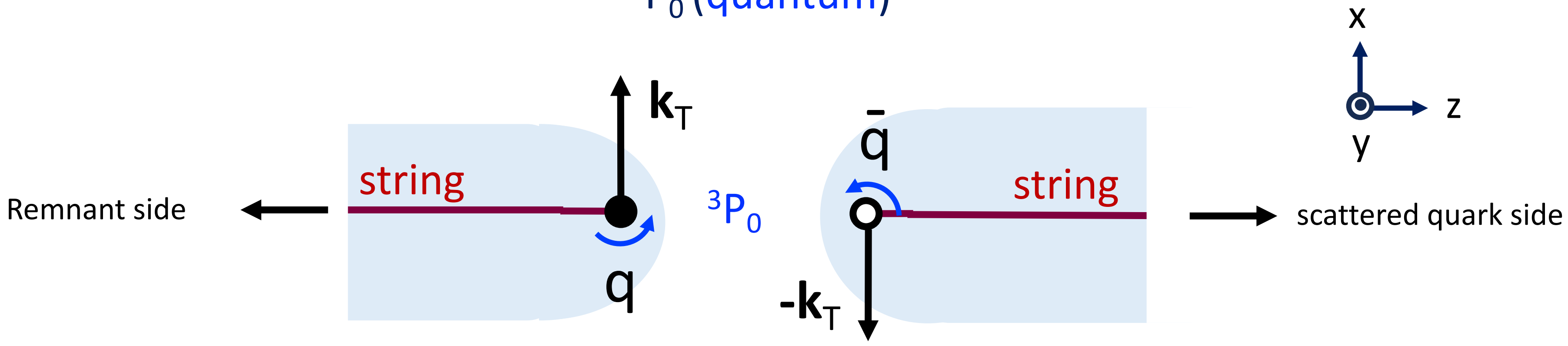
$$\vec{J} = \vec{L} + \vec{S} = \vec{0}$$

$L=1, S=1$

$q\bar{q}$ in the relative $^3P_0$ state

spin!

String breaking
$^3P_0$ (quantum)



spin-k_T correlation described by
"propagator" (2x2)

$$\Delta_q = \mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k}_T$$

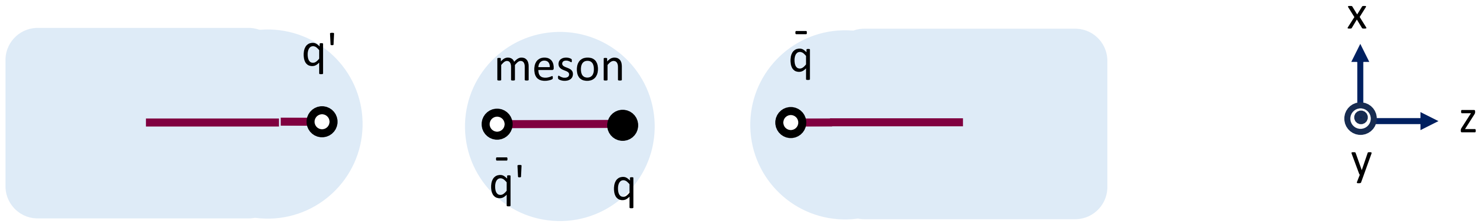
"complex mass" μ

2 free parameters
$\mathrm{Re}(\mu), \mathrm{Im}(\mu)$

AK, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin, PRD 97 (2018) 7, 074010

Meson production

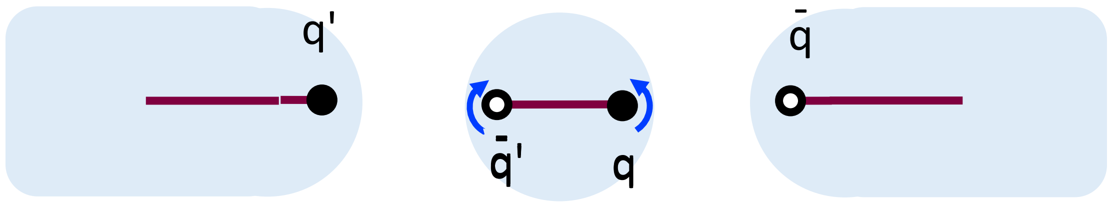
two successive string breakings

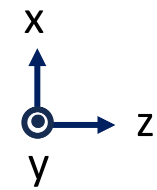


Pseudoscalar meson (PM) or vector meson (VM)

with probability $\mathrm{PM}:\mathrm{VM} \simeq 1:1$

Meson production
PM (quantum)



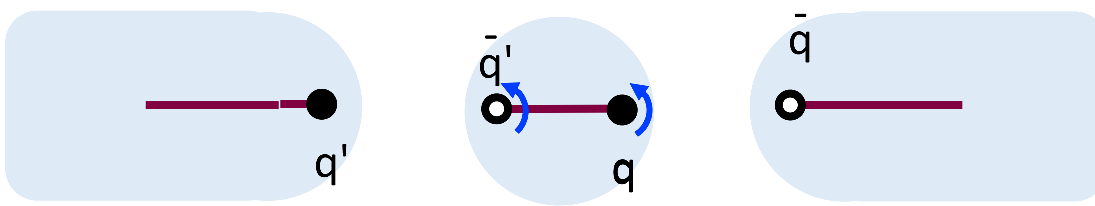


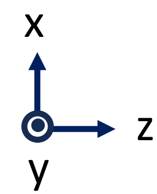
Pseudoscalar meson (PM) or vector meson (VM)
spin given by coupling (2x2)

$$\Gamma_{h=PM} = \sigma_z$$

no new free parameters

Meson production
VM (quantum)





Pseudoscalar meson (PM) or vector meson (VM)

spin given by coupling (2x2)

$$\Gamma_{h=VM} = G_T \vec{\sigma}_T \sigma_z \cdot \vec{V}^{*}{}_T + G_L 1 V_L^{*}$$

2 new free parameters:

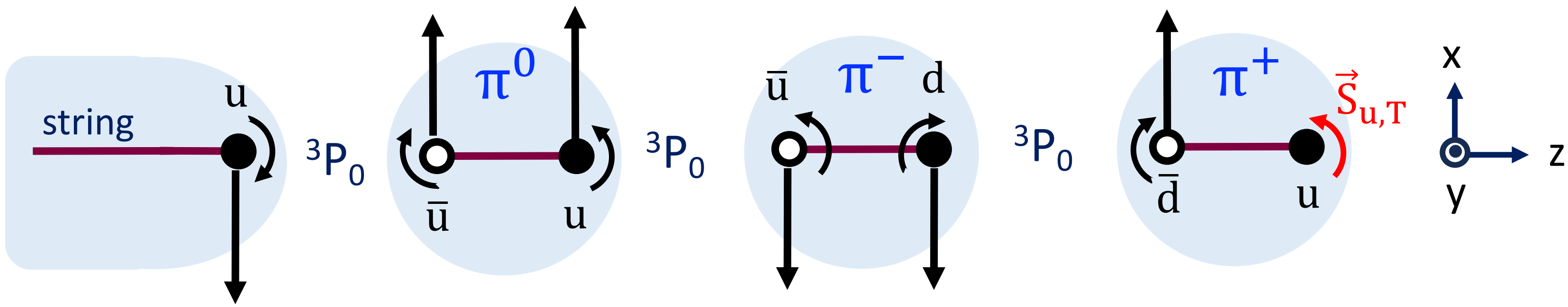
1. Probability VM has Longitudinal Polarization $f_L = \left|\frac{G_L}{G_T}\right|^2 / [2 + \left|\frac{G_L}{G_T}\right|^2]$

2. Interference between L and T polarizations $\theta_{LT} = \arg G_L/G_T$

AK, X. Artru, A. Martin, PRD 104 (2021) 11, 114038

Spin correlations in hadronization

X. Artru [DSPIN 2009]



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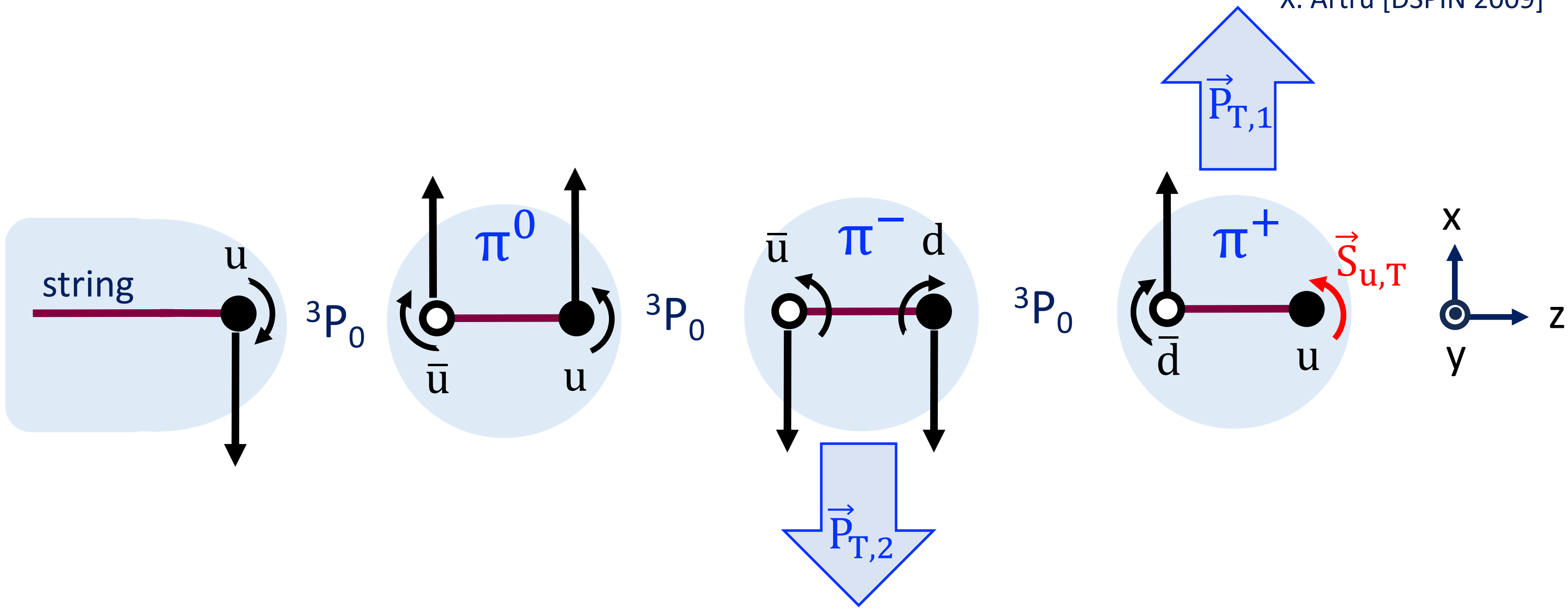
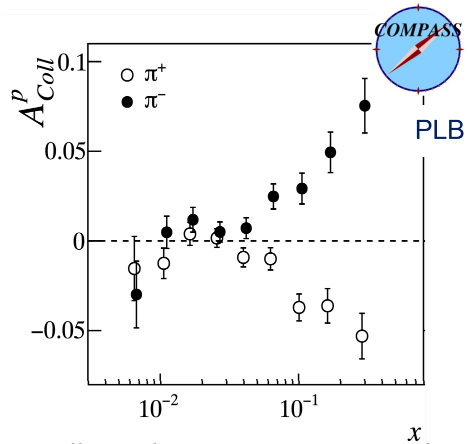


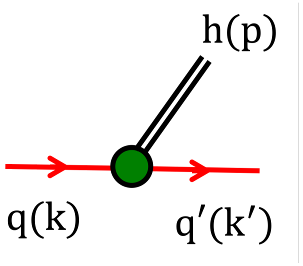
Collins effect of opposite sign for π^+ and π^-



PLB 717 (2012) 376

"quantum" string + $^3P_0$

Quark splitting matrix: Lund string fragmentation ⊗ spin



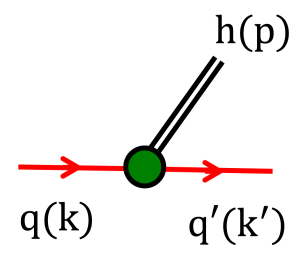
Pythia

$$T_{q',h,q} \propto C_{q',h,q} \; D_h(M^2) \left(\frac{1-Z_+}{\varepsilon_h^2}\right)^{\frac{a}{2}} \exp\left[-\frac{b_L \varepsilon_h^2}{2Z_+}\right] N_a^{-\frac{1}{2}}(\varepsilon_h^2) \; e^{-\frac{b_T k'^2_T}{2}}$$

AK, Artru, Martin, PRD 104, 114038 (2021)

"quantum" string + $^3P_0$

Quark splitting matrix: Lund string fragmentation $\otimes$ spin



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$$\otimes\;\; [\mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k'}_T] \qquad \Gamma_{h,s_h}$$

$^3P_0$ string breaking — q-h-q’ coupling

4 free parameters:
$\mathrm{Re}(\mu), \mathrm{Im}(\mu), f_L, \theta_{LT}$

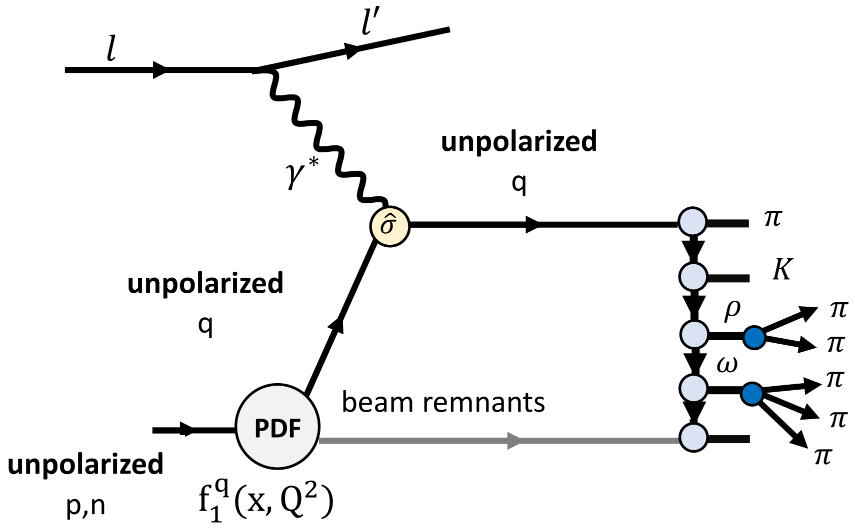
AK, Artru, Martin, PRD 104, 114038 (2021)

Implementation in Pythia for DIS

AK, L. Lönnblad, CPC ***272*** *(2022) 108234;*
CPC ***292*** *(2023) 108886*

Spin in Pythia for DIS: StringSpinner

- ❑ Pythia sets up PDFs, generates hard scattering and ties string
- ❑ Trace endpoint quark polarization starting from target
- ❑ Apply string+$^3P_0$



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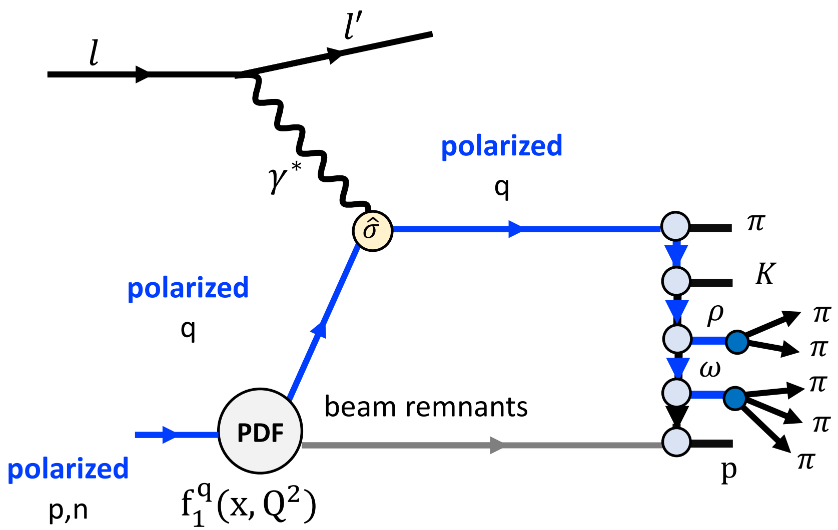

Transversity $h_1^q(x)$
or arbitrary polarization of quarks

AK, L. Lönnblad, CPC **272** (2022) 108234;
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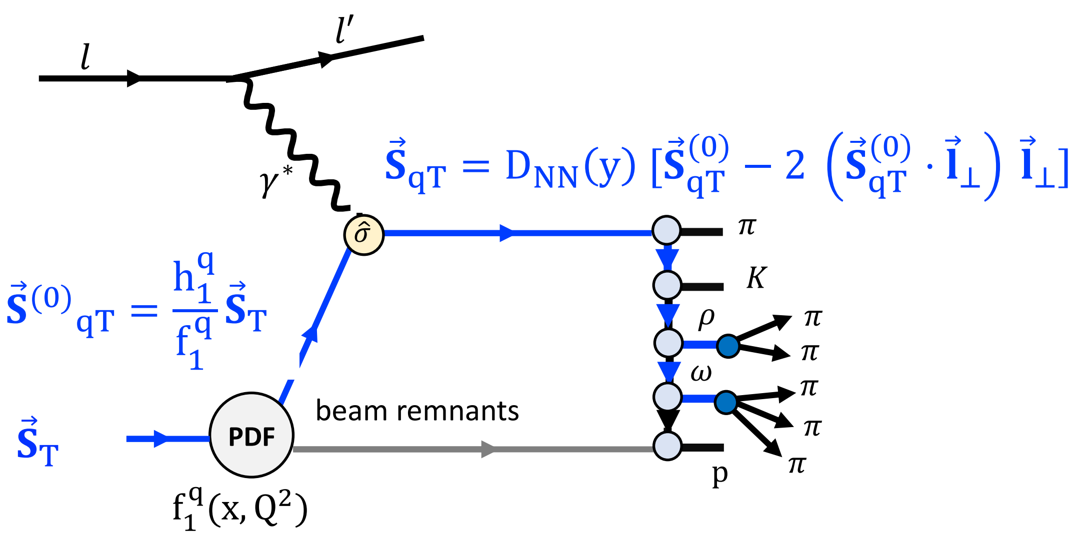

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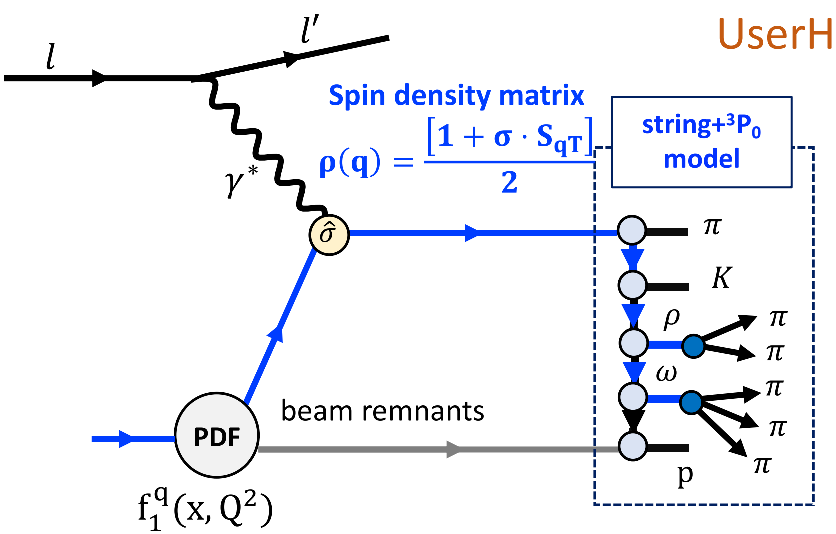
UserHooks:: setStringEnds



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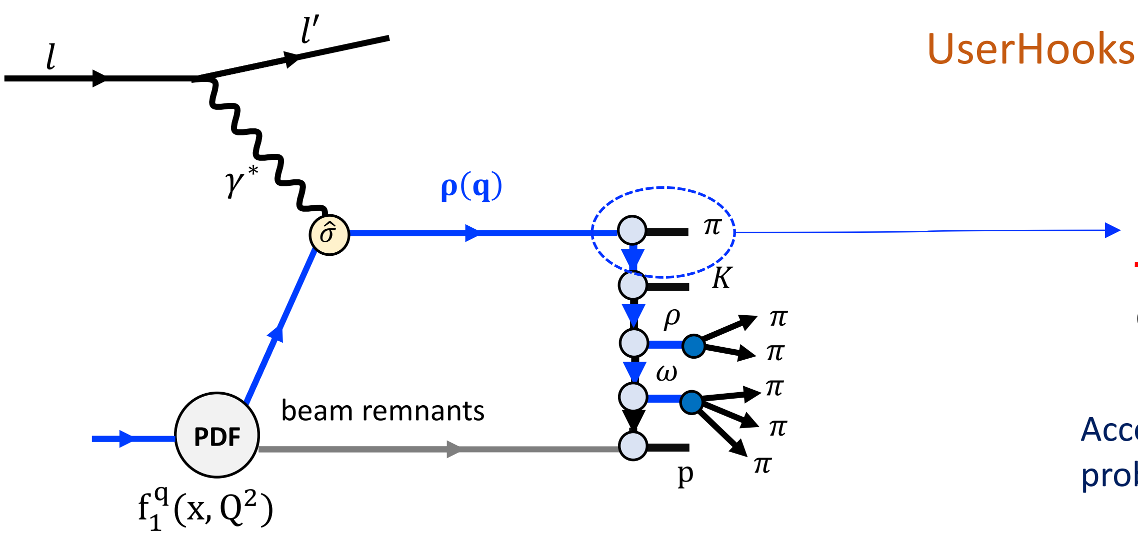
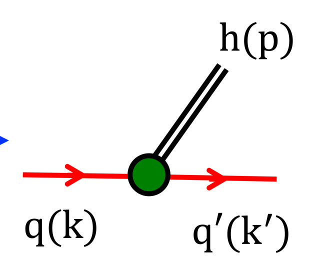


UserHooks:: doVetoFragmentation



Accept splitting with probability

$$w = \frac{dP_{spin}(q \to h + q')}{dP_{no\ spin}(q \to h + q')} = \frac{\mathrm{Tr}_{q'}\ T_{q',h,q}\ \rho(q) T^{\dagger}_{q',h,q}}{\frac{1}{2}\mathrm{Tr}_{q'}\ T_{q',h,q}\ T^{\dagger}_{q',h,q}}$$

Spin in Pythia for DIS: StringSpinner

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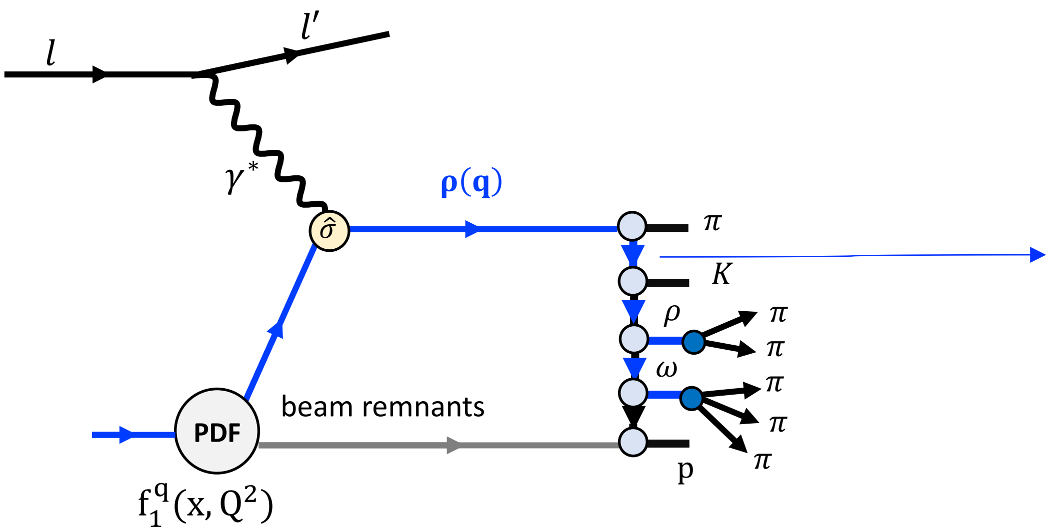

Evaluate spin density matrix of next quark q’

$$\rho(q') \propto T_{q',h,q}\, \rho(q)\, T^{\dagger}_{q',h,q}$$

Spin in Pythia for DIS: StringSpinner

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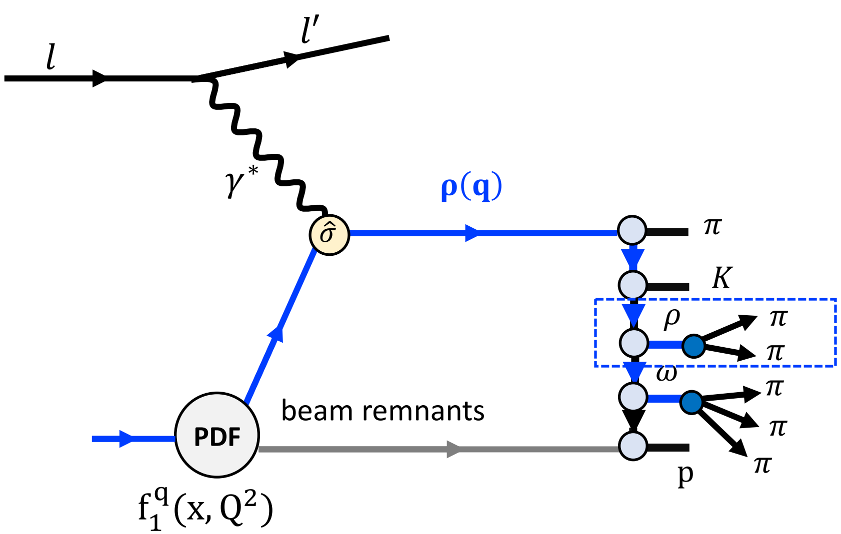


DecayHandler class

branching ratios, decay channel from Pythia

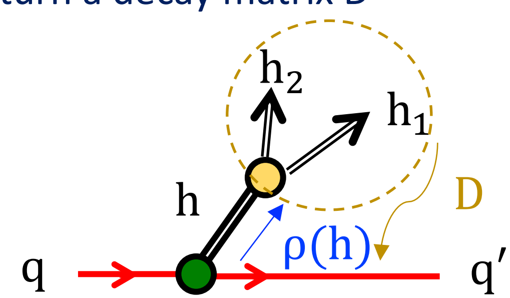
angular distributions externally

Collins-Knowles recipe (see backup)

i) calculate $\rho(h)$

ii) decay h polarized

iii) return a decay matrix D



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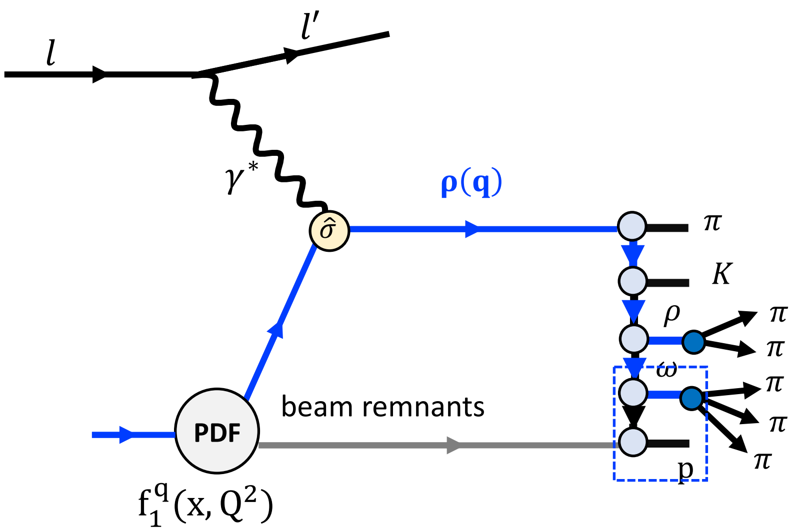


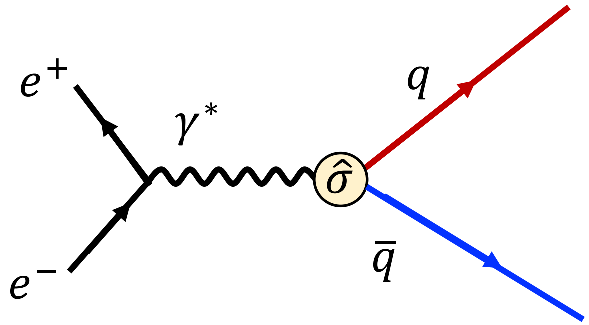
UserHooks::
doVetoFragmentation/doVetoFinalTwo

for the final two hadrons

Implementation in Pythia for e^+e^-

AK, X. Artru, PRD 109 (2024) 5, 05402
AK, L. Lönnblad, A. Martin, PRD 110 (2024) 7, 074029

Recursive recipe for e^+e^-



Steps:

1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. Exit condition

Recursive recipe for e^+e^-

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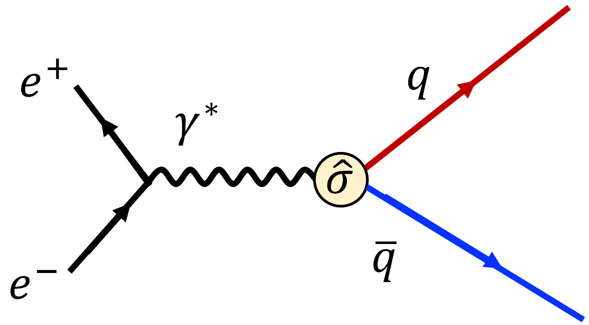
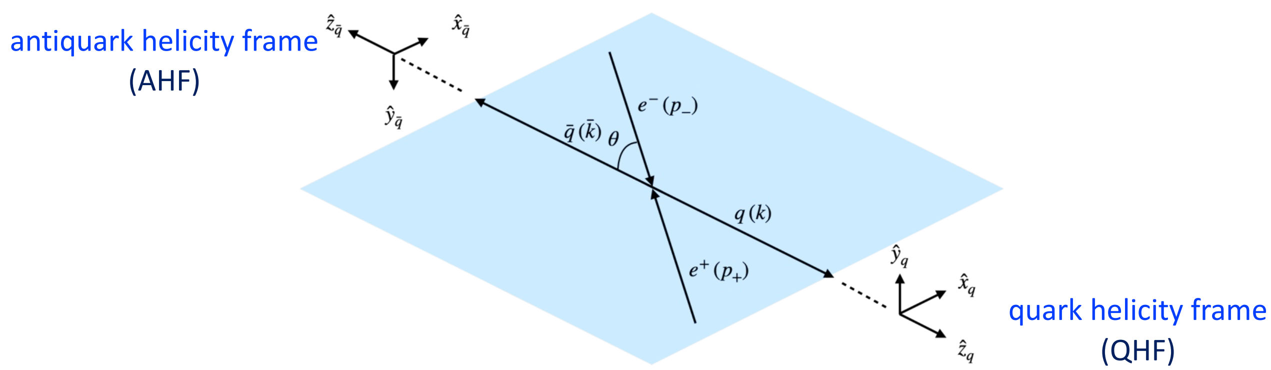


Set up the scattering $e^+e^- \to q\bar{q}$ in the c.m.s

generate the quark flavors and kinematics using differential cross section



Recursive recipe for e^+e^-

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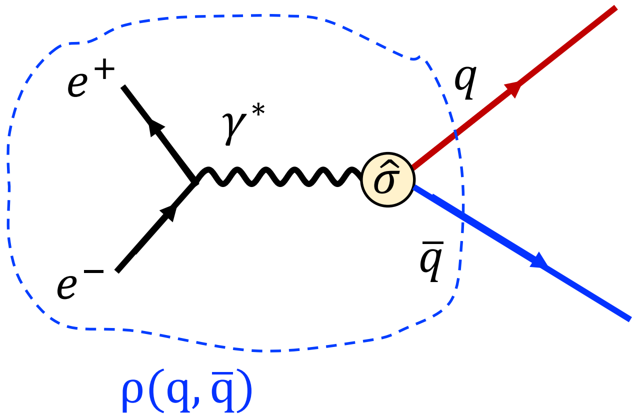
5. Hadron emission from $\bar{q}$
6. Exit condition



- Set up the joint spin density matrix of the $q\bar{q}$ pair

$$\rho(q,\bar{q}) = C^{q\bar{q}}_{\alpha\beta} \quad \sigma^\alpha_q \otimes \sigma^\beta_{\bar{q}}$$

correlation coefficients

Pauli matrices along QHF and AHF

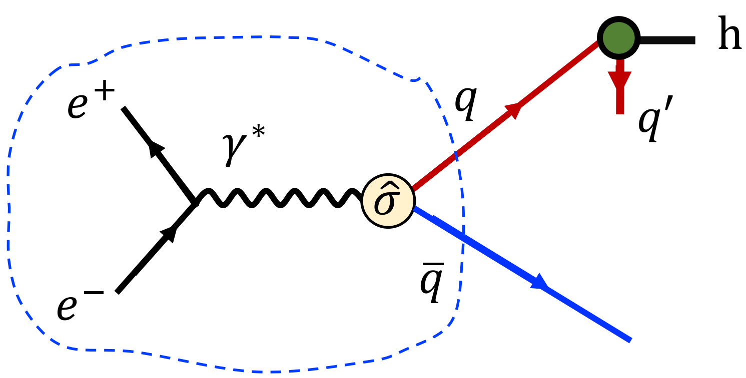
$\alpha = 0, x_q, y_q, z_q$

$\beta = 0, x_{\bar{q}}, y_{\bar{q}}, z_{\bar{q}}$

For γ^* exchange

$$\rho(q,\bar{q}) \propto 1_q \otimes 1_{\bar{q}} - \sigma^z_q \otimes \sigma^z_{\bar{q}} + \frac{\sin^2\theta}{1+\cos^2\theta}\left[\sigma^x_q \otimes \sigma^x_{\bar{q}} + \sigma^y_q \otimes \sigma^y_{\bar{q}}\right]$$

Recursive recipe for e^+e^-



Steps:
1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from *q*
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. Exit condition

- ❑ Emit the first hadron using the splitting function (emission probability density)

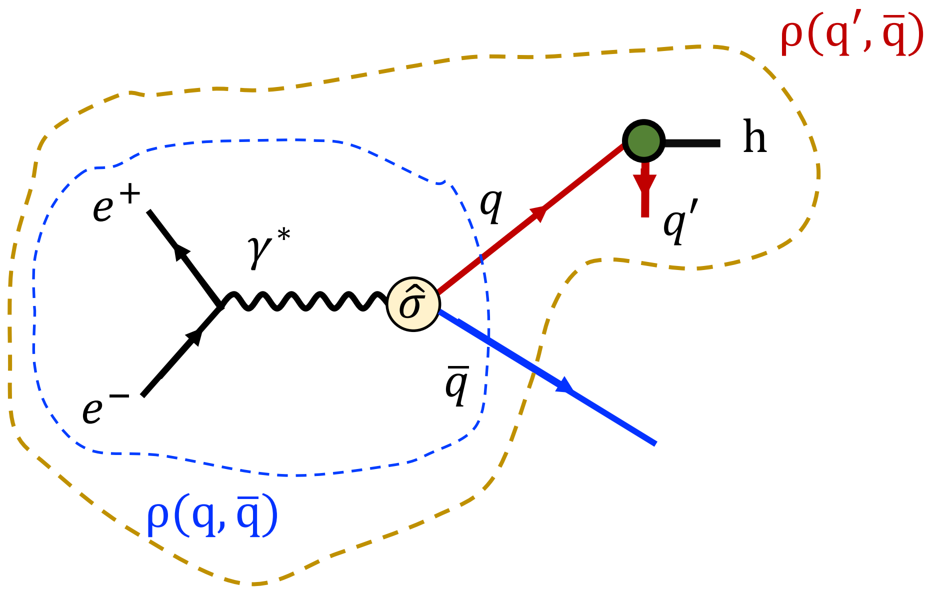
$$\frac{dP(q \to h + q'; q\bar{q})}{dZ_+ Z_+^{-1} d^2 p_T} = \mathrm{Tr}_{q'\bar{q}} \mathbf{T}_{q',h,q}\, \rho(q,\bar{q})\, \mathbf{T}^\dagger_{q',h,q} = F_{q',h,q}(Z_+, \mathbf{p}_T; \mathbf{k}_T, C^{q\bar{q}})$$

$$\mathbf{T}_{q',h,q} \equiv T_{q',h,q} \otimes 1_{\bar{q}}$$

in the QHF

- ❑ For VM emission need also to handle the polarized decay → backup

Recursive recipe for e^+e^-



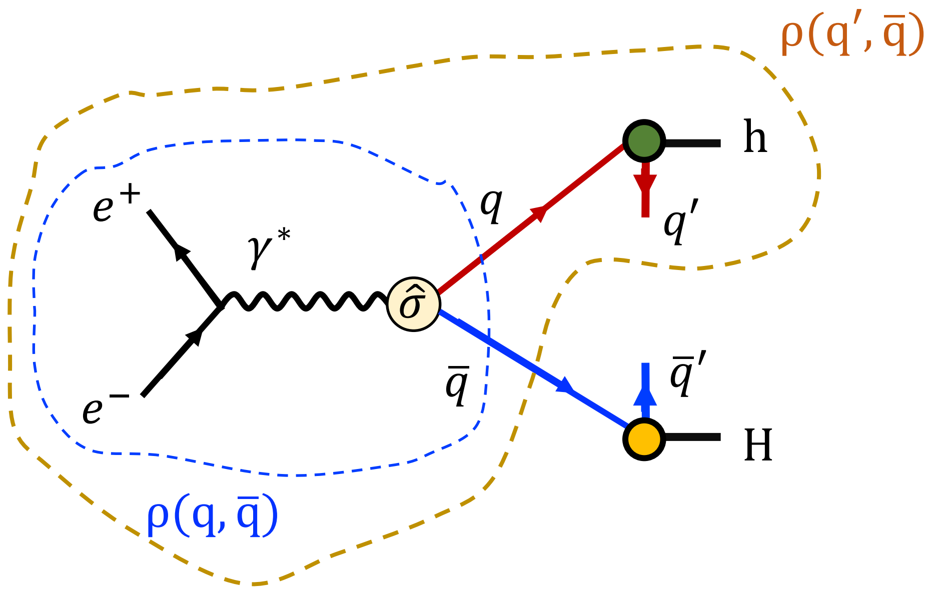
Steps:
1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. **Update density matrix**
5. Hadron emission from $\bar{q}$
6. Exit condition

- Evaluate the spin density matrix $\rho(q'\bar{q})$

$$\rho(q', \bar{q}) = \mathbf{T}_{q',h,q} \quad \rho(q, \bar{q}) \quad \mathbf{T}^{\dagger}_{q',h,q}$$

includes the information on the emission of h

Recursive recipe for e^+e^-



Steps:
1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. **Hadron emission from $\bar{q}$**
6. Exit condition

- Emit a hadron from the $\bar{q}$ side using the splitting function

Depend on the azimuthal angle h

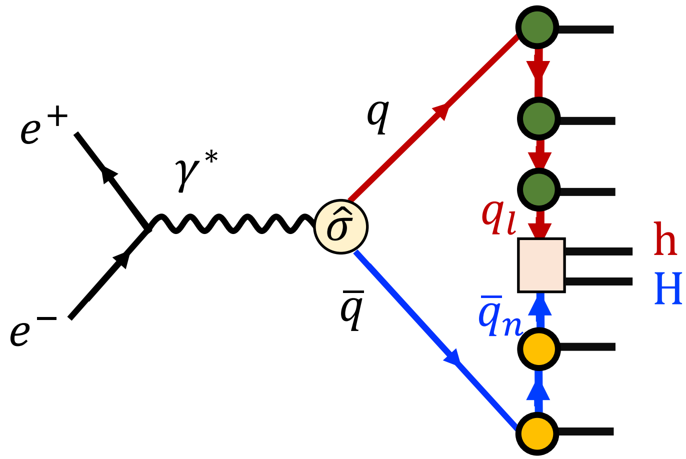
$$\frac{dP(\bar{q}\to H+\bar{q}';q'\bar{q})}{dZ_-Z_-^{-1}d^2P_T}=\mathrm{Tr}_{q'\bar{q}'}\mathbf{T}_{\bar{q}',H,\bar{q}}\,\rho(q',\bar{q})\,\mathbf{T}^{\dagger}_{\bar{q}',H,\bar{q}}=F_{\bar{q}',H,\bar{q}}(Z_-,P_T;\bar{k}_T,C^{q'\bar{q}})$$

Expressed in the AHF

conditional probability of emitting H, having emitted h
→ correlations between the transverse momenta

[Collins NPB, 304:794–804, 1988, Knowles NPB, 310:571–588, 1988]

Recursive recipe for e^+e^-



Steps:

1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. **Exit condition**

[AK, X. Artru, PRD 109 (2024) 5, 054029]

- Iterate until the exit condition is called and the last quark pair is hadronized
  more details in PRD 109 (2024) 5, 054029

Tuning of StringSpinner

with A. Buckley, C. Gutschow, L. Lönnblad (ongoing)

Tuning of StringSpinner: procedure

- Sample $\vec{p}_i = (\mathrm{Re}(\mu), \mathrm{Im}(\mu), f_L, \theta_{LT})_i$ (100 times)

  - for each $\vec{p}_i$
    run Pythia+StringSpinner
    calculate observables O_1, O_2 ... (Collins, 2h asymmetries)

- Parametrize $O_b^{MC}(\vec{p})$ as function of $\vec{p}$ for each bin b
- Minimize

$$X^2 = \sum_O \sum_b \frac{\left(O_b^{MC}(\vec{p}) - O_b^D\right)^2}{\sigma^2_{O_b^{MC}} + \sigma^2_{O_b^D}}$$

- Obtain $\vec{p}_{tune}$

PROFESSOR 2

A. Buckley et al., EPJ C 65 (2010) 331-357

Tuning of StringSpinner: data

- SIDIS with $p^{\uparrow}$ target

Collins asymmetries

COMPASS	$\pi^{\pm}, K^{\pm}, K^{0}$	PLB 717 (2012) 376
	ρ^{0}	PLB 843 (2023) 137950
HERMES	$\pi^{\pm}, K^{\pm}, \pi^{0}$	PLB 693 2010) 11

2h asymmetries

COMPASS	$\pi\pi, \pi K, KK$	PLB 845 (2023) 138155
HERMES	$\pi\pi$	JHEP 06 (2008) 017

- $e^{+}e^{-}$ annihilation

Collins asymmetries

BELLE	$A_{12}^{UL(UC)}$	$\pi\pi$	PRD 100, 092008 (2019)
BELLE	$A_{12}^{UL(UC)}, A_{0}^{UL(UC)}$	$\pi\pi$	PRD 78, 032011 (2008)
BABAR	$A_{0}^{UL(UC)}(P_{T0})$	$\pi\pi$	PRD 90, 052003 (2014)
	$A_{12}^{UL(UC)}$	$\pi\pi, \pi K, KK$	PRD 92, 111101(R) (2015)
	$A_{0}^{UL(UC)}$	$\pi\pi, \pi K, KK$	PRD 92, 111101(R) (2015)

Tuning of StringSpinner: data

- SIDIS with $p^{\uparrow}$ target

Collins asymmetries

COMPASS	$\pi^{\pm}, K^{\pm}, K^0$ ρ^0
HERMES	$\pi^{\pm}, K^{\pm}, \pi^0$

2h asymmetries

COMPASS	$\pi\pi$, πK, KK
HERMES	$\pi\pi$

- e^+e^- annihilation

Collins asymmetries

BELLE	$A_{12}^{UL(UC)}$	$\pi\pi$
BELLE	$A_{12}^{UL(UC)}, A_0^{UL(UC)}$	$\pi\pi$
BABAR	$A_0^{UL(UC)}(P_{T0})$	$\pi\pi$
	$A_{12}^{UL(UC)}$	$\pi\pi$, πK, KK
	$A_0^{UL(UC)}$	$\pi\pi$, πK, KK

Tune

~680 data points

X2/ndf ~ 2.2

$\mathrm{Re}(\mu) = 0.11$

$\mathrm{Im}(\mu) = 0.33$

$f_L = 0.83$

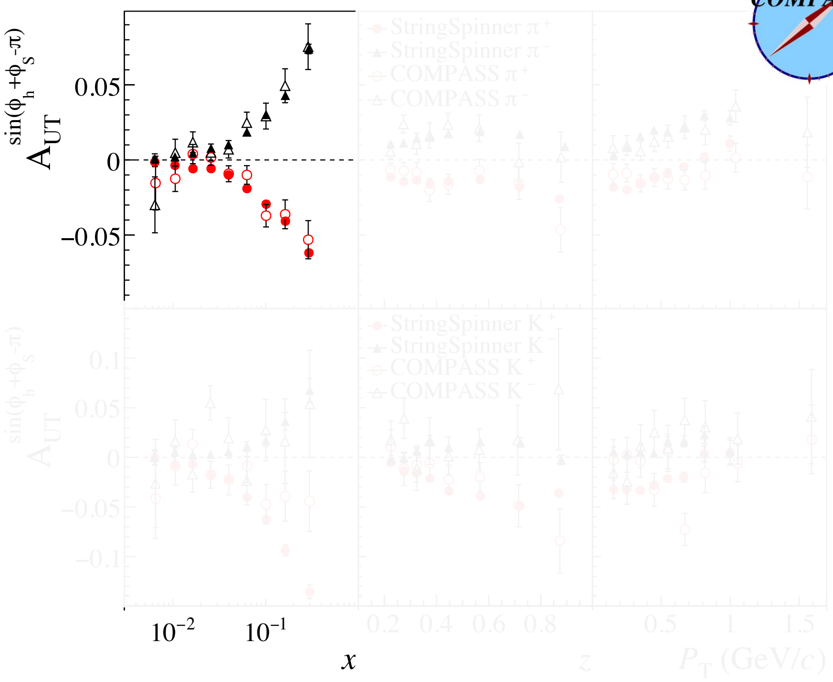
$\theta_{LT} = 0.09$

preliminary

Results from the tune

with A. Buckley, C. Gutschow, L. Lönnblad (ongoing)

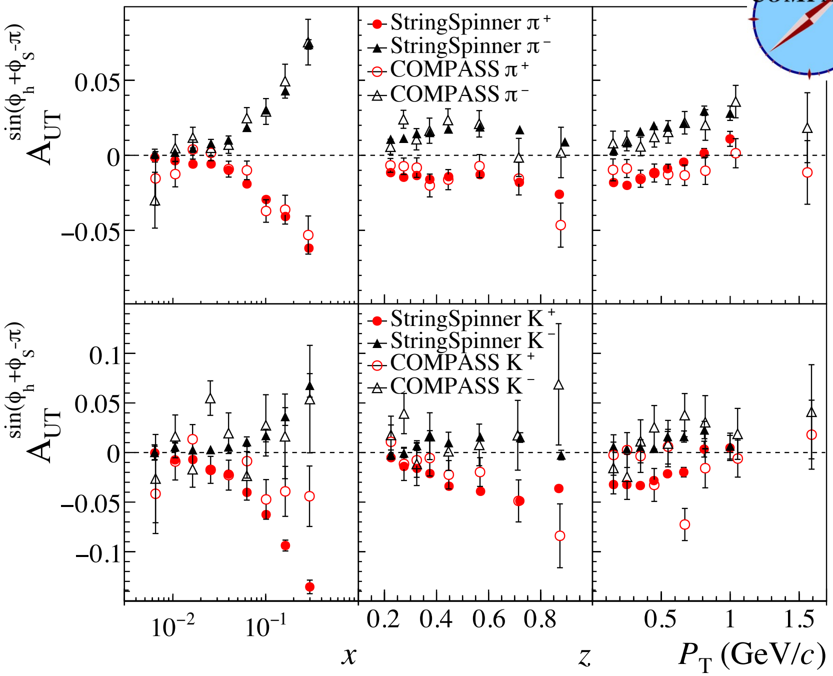
TSA in SIDIS: Collins



PLB 717 (2012) 376

Collins asymmetry @ COMPASS

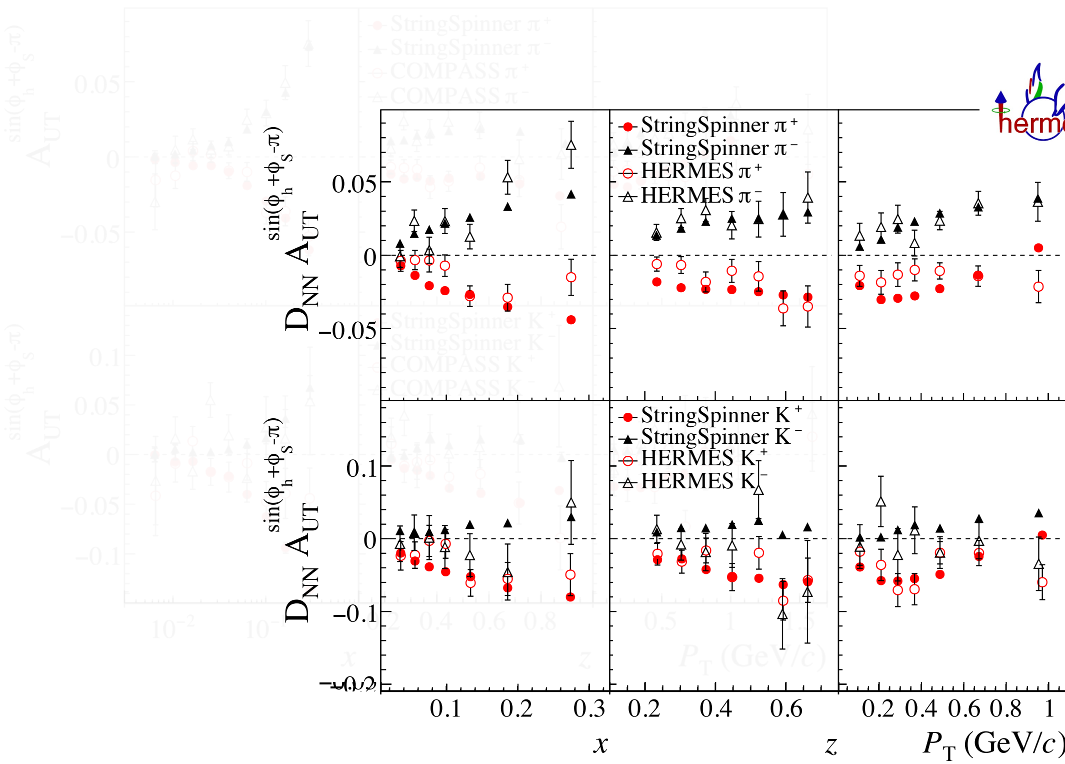
TSA in SIDIS: Collins



PLB 717 (2012) 376

Collins asymmetry @ COMPASS

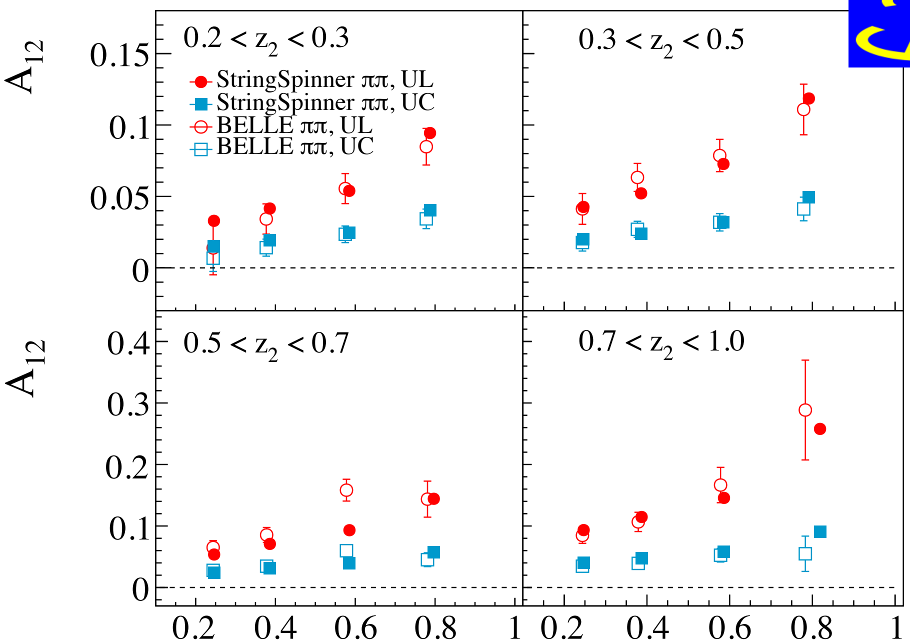
TSA in SIDIS: Collins

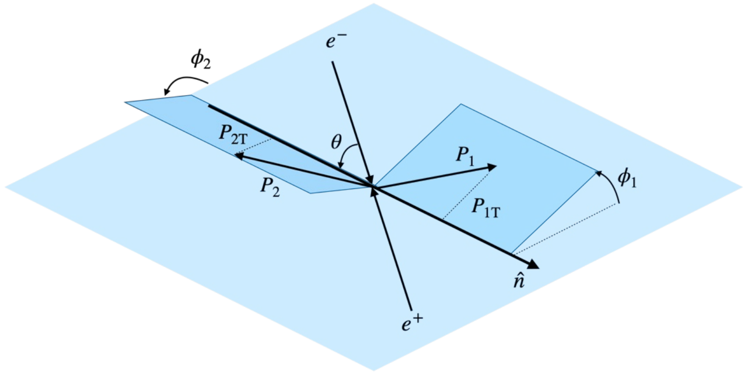


PLB 693 2010) 11

Collins asymmetry @ HERMES

e^+e^-: Collins



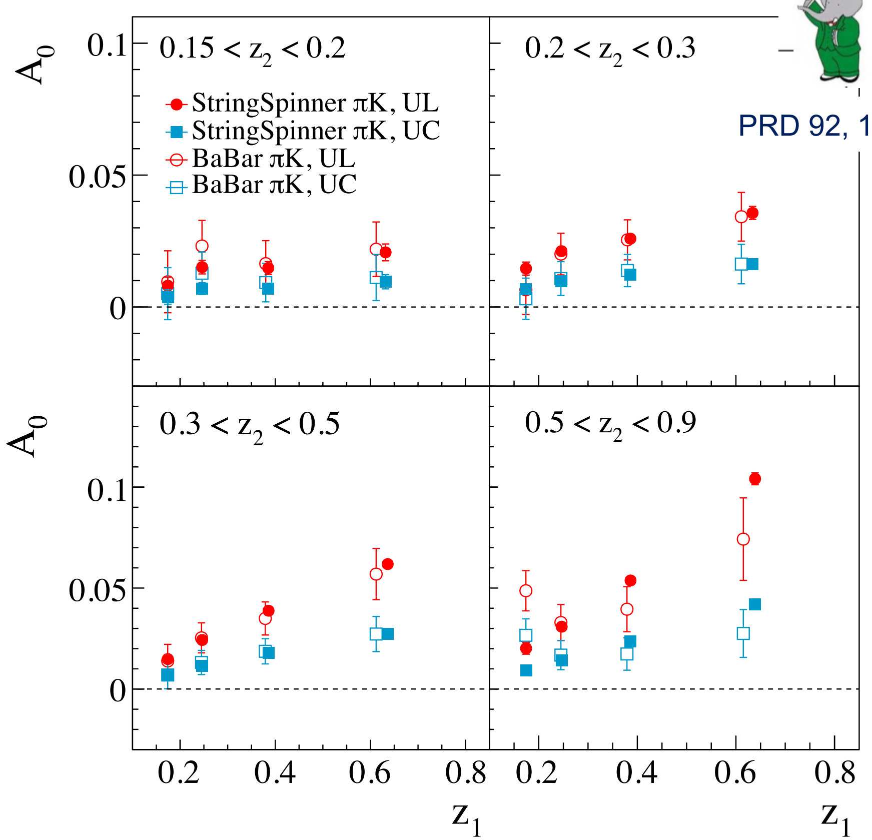


$$d\sigma^{h_1 h_2} \propto 1 + \hat{a}_{NN}(\theta)\, A_{12} \cos(\phi_1 + \phi_2) + \cdots$$

$$A_{12} \simeq \frac{\sum_q e_q^2 H_{1q}^{\perp h_1} \times H_{1q}^{\perp h_2}}{\sum_q e_q^2 D_{1q}^{h_1} \times D_{1q}^{h_2}}$$

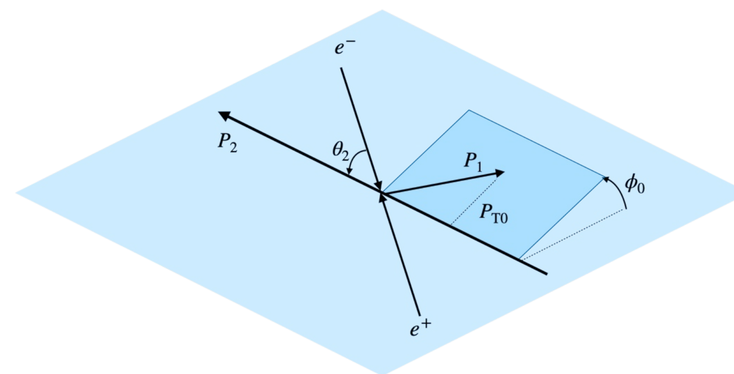
Back-to-back pions @ BELLE

e^+e^-: Collins



Back-to-back pions and kaons @ BABAR

PRD 92, 111101(R) (2015)



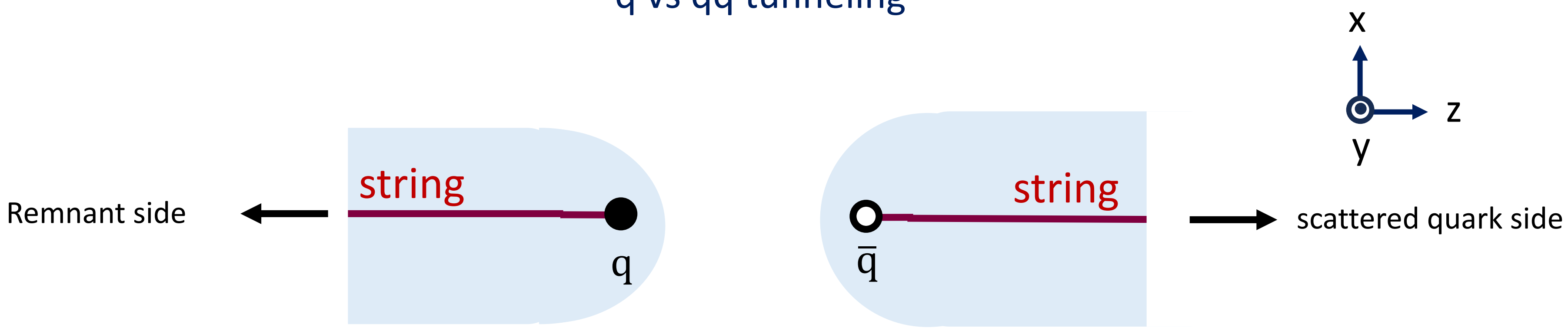
$$d\sigma^{h_1 h_2} \propto 1 + \hat{a}_{NN}(\theta_2)\, A_0 \cos(2\phi_0) + \cdots$$

$$A_0 \simeq \frac{\sum_q e_q^2\, C[w\, H_{1q}^{\perp h_1} \times H_{1q}^{\perp h_2}]}{\sum_q e_q^2\, C[D_{1q}^{h_1} \times D_{1q}^{h_2}]}$$

Production of spin-1/2 baryons

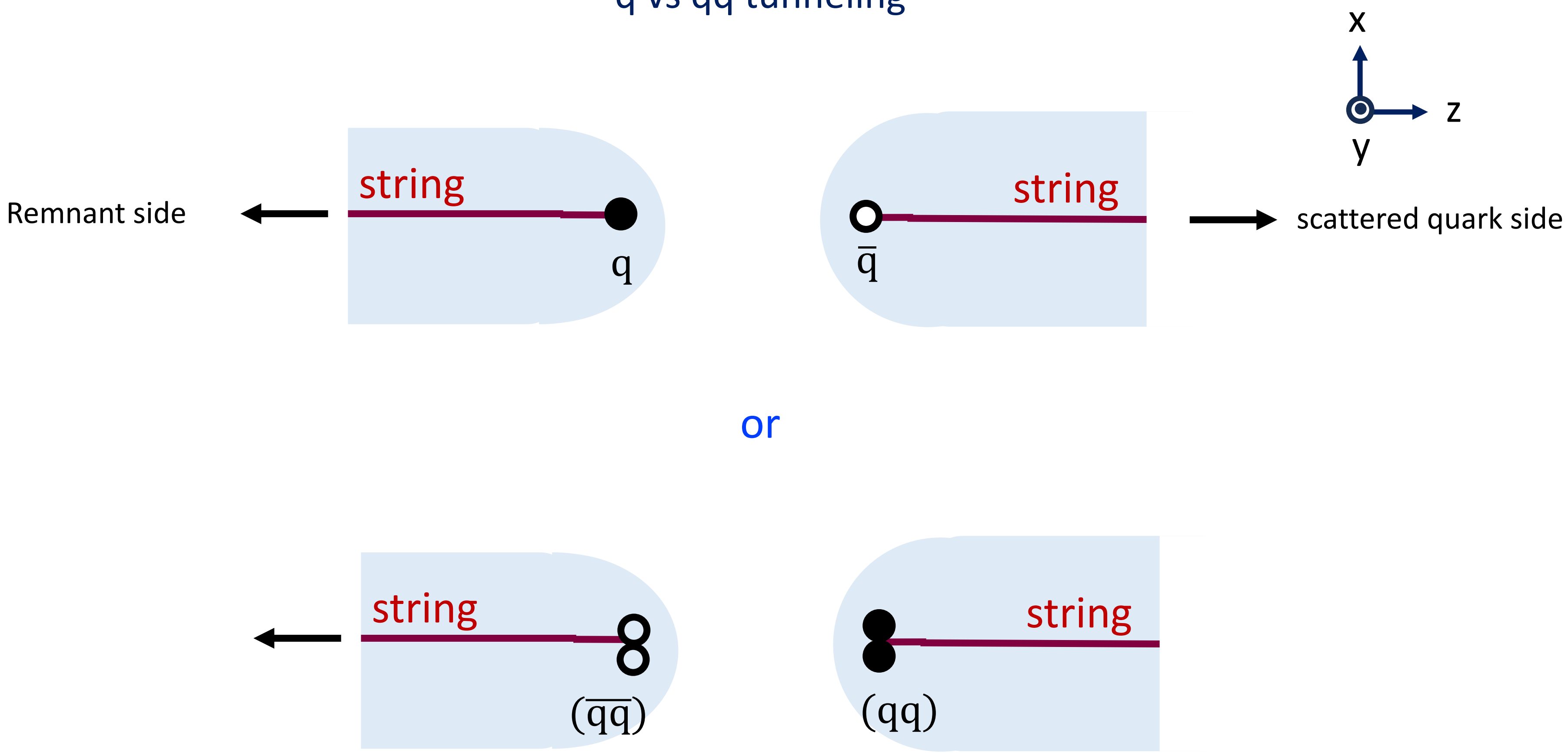
AK, X. Artru, PRD 113 (2026) 3, 034007

String breaking
q vs qq tunneling



or

String breaking
q vs qq tunneling



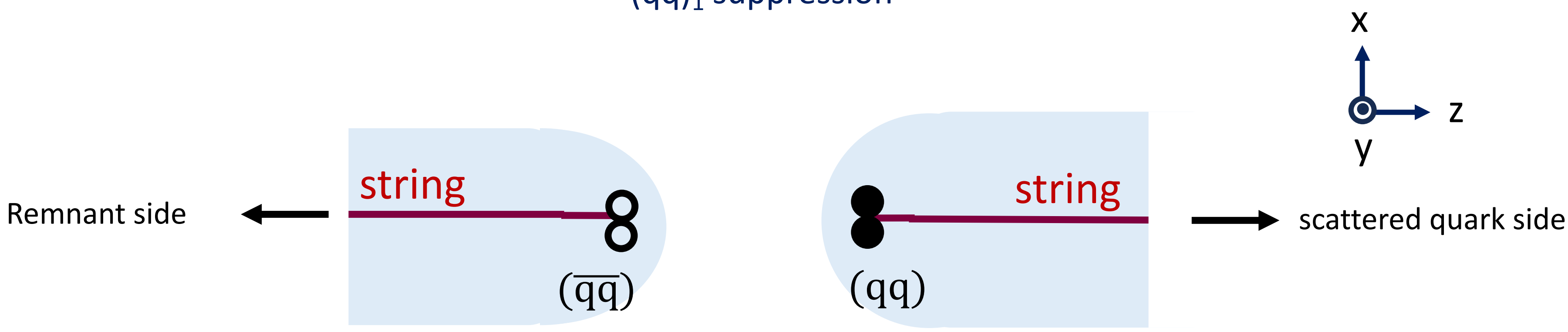
diquark tunneling suppressed w.r.t quark tunneling

$$\frac{P_{qq}}{P_q} \approx 0.1$$

Pythia 8

String breaking

$(qq)_1$ suppression



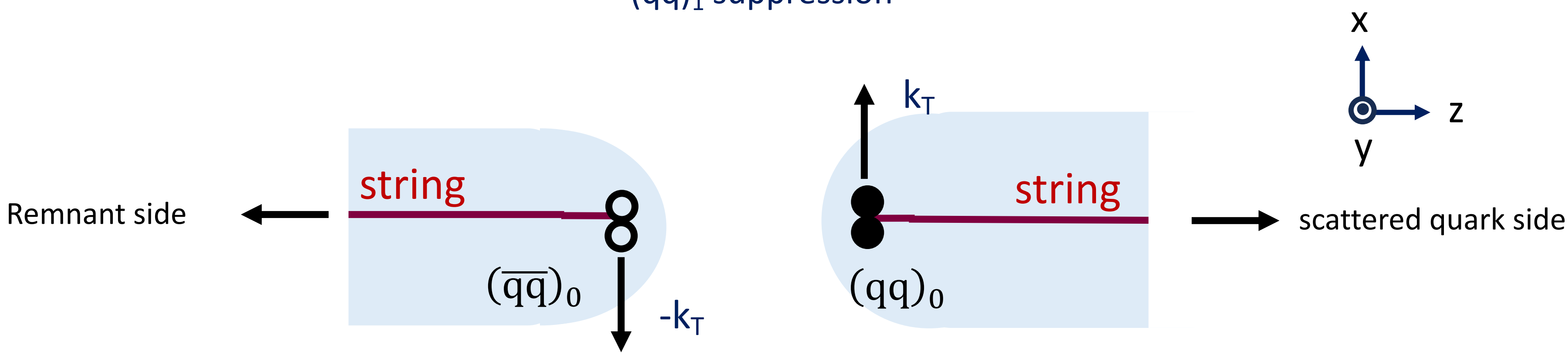
Suppression of spin-1 diquarks

$$\frac{P_{(qq)_1}}{P_{(qq)_0}} \approx 0.03$$

Pythia 8

String breaking

$(qq)_1$ suppression



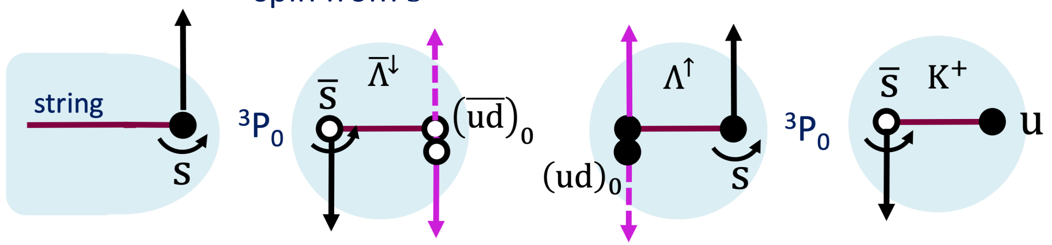
Local conservation of k_T for $(qq)_0$

Local conservation of $\vec{J} = \vec{L} + \vec{S}$ for $(qq)_1$

$^5D_0$ mechanism *AK, X. Artru, PRD 113 (2026) 3, 034007*

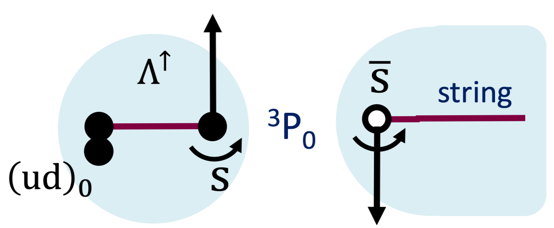
Hyperon production

$\overline{\Lambda}$ inherits transverse spin from $\bar{s}$



~large x_F
CFR

Λ inherits transverse spin from s

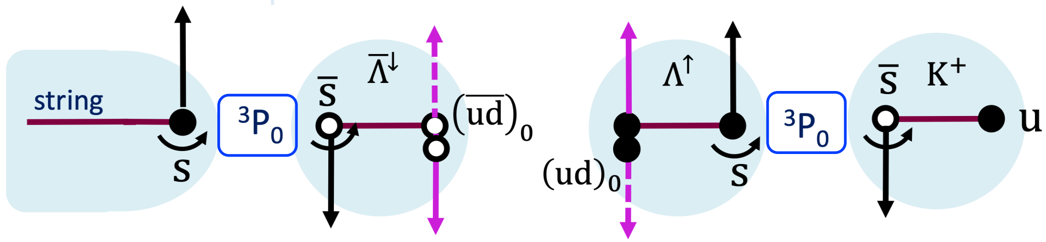


~negative x_F
TFR

Λ inherits transverse spin from s

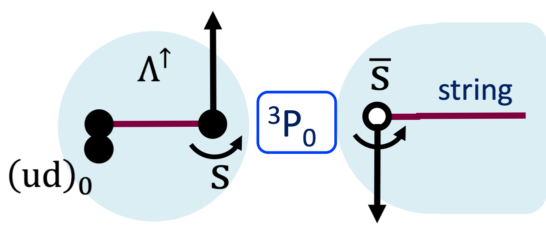
Hyperon production

$\bar{\Lambda}$ inherits transverse spin from $\bar{s}$



~large x_F CFR

Λ inherits transverse spin from s



~negative x_F TFR

Λ inherits transverse spin from s

$^3P_0$ breakings → spin parameters from Collins effect!

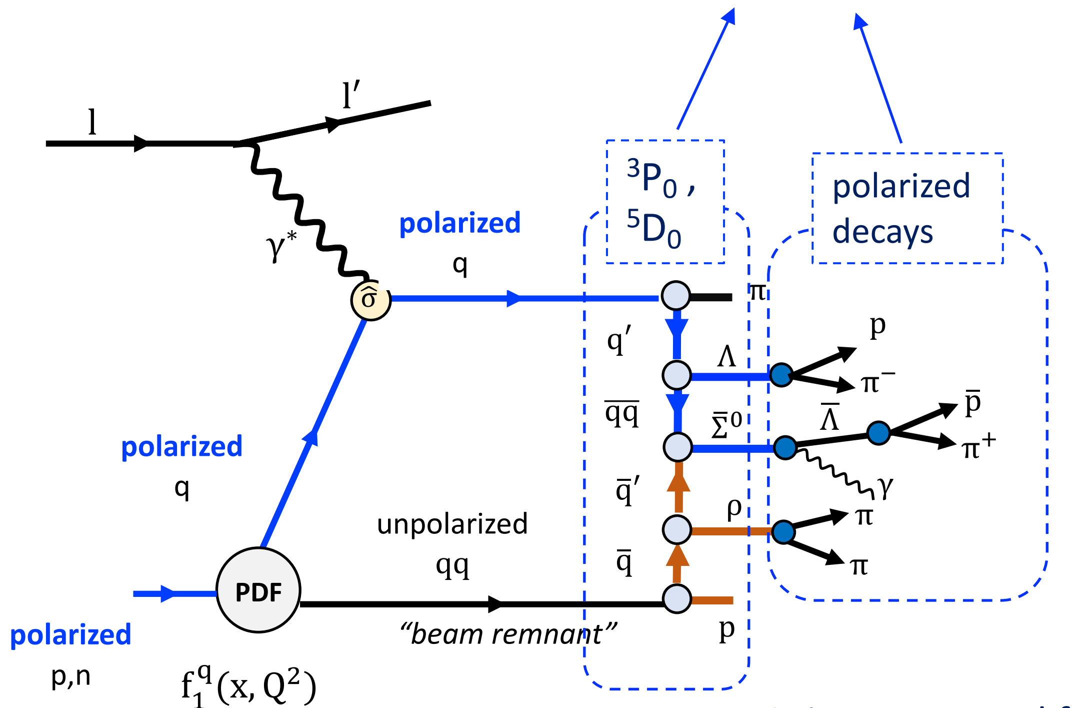
All this implemented in StringSpinner… (not public yet)

Implementation of the extended string+$^3P_0$ model in Pythia for DIS

- ❑ Extension of the existing StringSpinner package

parton showers off..

Using the corresponding
quantum mechanical amplitudes



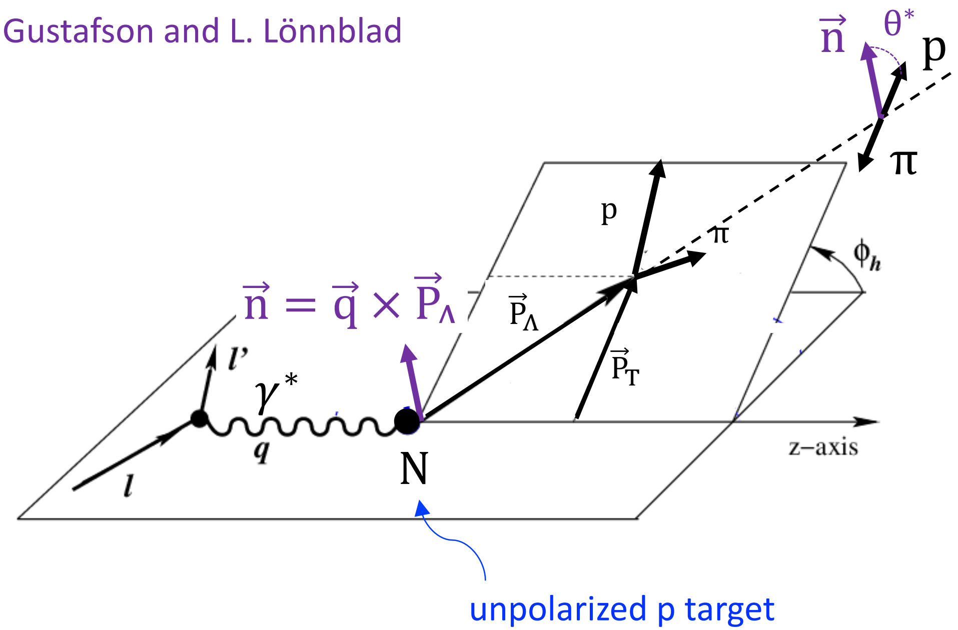
Transversity $h_1^q(x)$
or arbitrary polarization of quarks

Spin propagated from struck quark and remnant

→ *Collins-Knowles recipe (backup)*

Spontaneous polarization of Λ and $\bar{\Lambda}$

with G. Gustafson and L. Lönnblad

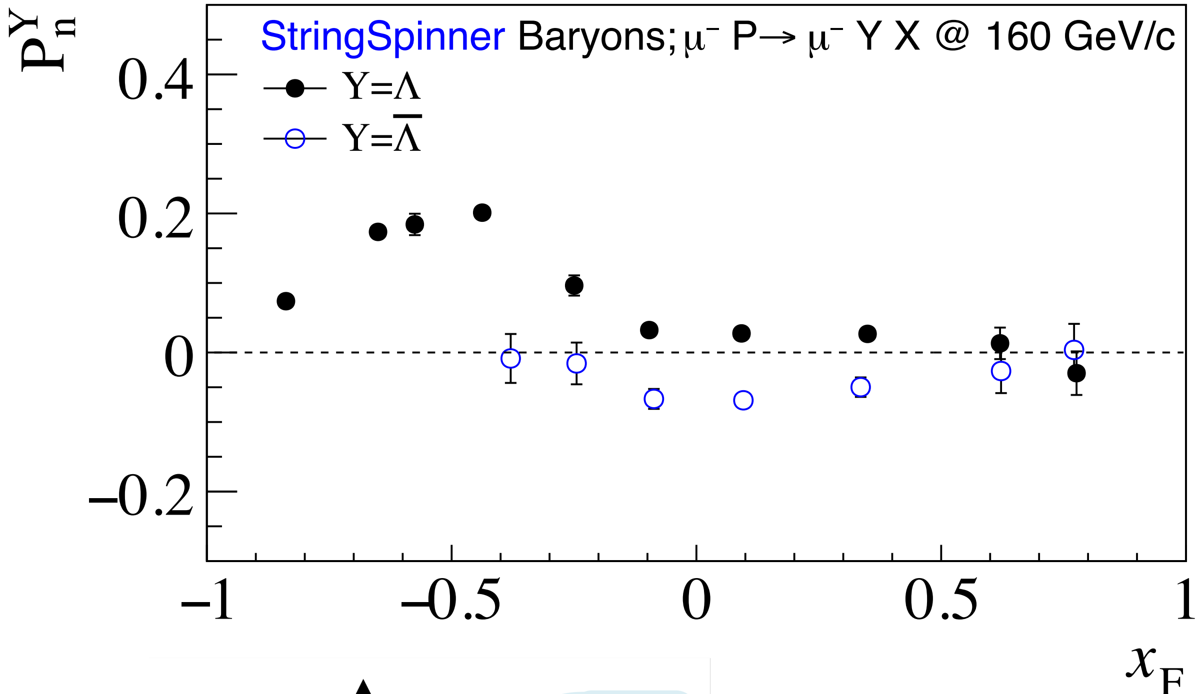


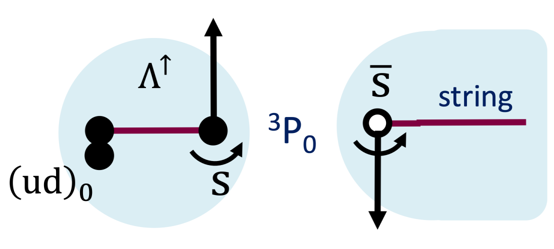
Extracted from the angular distribution of the decay proton in the Λ rest frame

$$\frac{dN_p}{d\cos\theta^*} \propto 1 + \alpha_Y \, P_n^Y \cos\theta^* \qquad \alpha_\Lambda \simeq 0.73, \;\; \alpha_{\bar{\Lambda}} \simeq -0.76 \quad \text{[PDG]}$$

$\Lambda, \bar{\Lambda}$ production in the TFR in DIS:

spontaneous polarization





Conclusions

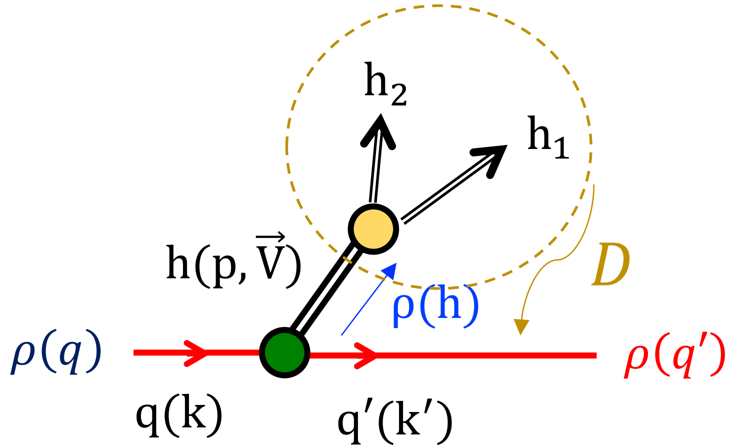
- Spin in Pythia via StringSpinner, using string+$^3P_0$
- Applied to DIS and e^+e^-
  tuning ongoing, results promising
- Baryon production included recently using a diquark based model
- String+$^3P_0$ and StringSpinner under active development
  connection of spin effects between PS and hadronization…

  we aim at preparing a MC with spin effects in all stages of the event generation

Backup

Vector meson emission in string+$^3P_0$

AK, Artru, Martin, PRD 104, 114038 (2021)



Emission probability $dP(q \to h + q') = \mathrm{Tr}\, \sum_{\vec{V}} T^{\vec{V}}_{q',h,q}\, \rho(q)\, T^{\vec{V}\dagger}_{q',h,q}\, dZZ^{-1} d^2\mathbf{p}_T$

Density matrix of VM $\rho_{ab}(h) = T^a_{q',h,q}\, \rho(q)\, T^{b\dagger}_{q',h,q}$

Decay of the VM $dN/d\Omega \propto M_{decay}(h \to h_1 h_2 ..)\ \rho(h)\ M^\dagger_{decay}(h \to h_1 h_2 ..)$

Decay matrix $D = M_{decay}(h \to h_1 h_2 ..)\, M^\dagger_{decay}(h \to h_1 h_2 ..)$

Collins '88, Knowles, '88

Propagation of quark spin $\rho(q') = T^a_{q',h,q}\ \ \rho(q)\ \ T^{b\dagger}_{q',h,q}\ \ D_{ba}(p_1, p_2, ..)/\ \mathrm{Tr}[..]$